U.S. DEPARTMENT OF COMMERCE
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PB-258 794-T

The Problem of Selecting the Number of Sampling Points and Frequency of Observations of Atmospheric Pollution

Environmental Protection Agency, Research Triangle Park, N C

1971

300022

EPA-TR.647-73J
APTIC 47616

MAIN ADMINISTRATION OF THE HYDROMETEOROLOGICAL SERVICE
USSR COUNCIL OF MINISTERS

PB 258 794-T

ORDER OF THE RED BANNER OF LABOR
MAIN GEOPHYSICAL OBSERVATORY imeni A. I. Boyeykov

WORKS

Issue 254

ATMOSPHERIC DIFFUSION AND AIR POLLUTION

: 140-151.

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Hydrometeorological Press
Leningrad 1971

REPRODUCED BY
NATIONAL TECHNICAL
INFORMATION SERVICE
U.S. DEPARTMENT OF COMMERCE
SPRINGFIELD, VA. 22161

BIBLIOGRAPHIC DATA SHEET	1. Report No. EPA TR 73-647J	2.	3. Recipient's Accession No.
4. Title and Subtitle The problem of selecting the number of sampling points and frequency of observations of atmospheric pollution			5. Report Date 1971 6.
7. Author(s) B.B. Goroshko			8. Performing Organization Rept. No.
9. Performing Organization Name and Address TRANSLATED FROM RUSSIAN BY EPA			10. Project/Task/Work Unit No. 11. Contract/Grant No.
12. Sponsoring Organization Name and Address Translation Service Office of Administration - Library Research Triangle Park, NC 27711			13. Type of Report & Period Covered 14.

15. Supplementary Notes

ATMOSPHERIC DIFFUSION AND AIR POLLUTION 1971, pp.140-151

16. Abstracts

17. Key Words and Document Analysis. 17a. Descriptors

EPAISD

17b. Identifiers/Open-Ended Terms

AIR POLLUTION - MEASUREMENT METHODS

17c. COSATI Field/Group 13B 68A

PRICES SUBJECT TO CHANGE

18. Availability Statement	19. Security Class (This Report)	21. No. of Pages
THIS TRANSLATION WAS MADE FROM A NON-COPYRIGHTED TEXT	UNCLASSIFIED	20
	20. Security Class (This Page) UNCLASSIFIED	22. Price $3.50

TR 647-73 J
APTIC 47616

THE PROBLEM OF SELECTING THE NUMBER OF SAMPLING POINTS AND FREQUENCY OF OBSERVATIONS OF ATMOSPHERIC POLLUTION

[K voprosu o vybore kolichestva punktov otbora prob i chastote nablyudeniy za zagryazneniyem atmosferey]

B.B. Goroshko

Atmospheric diffusion and air pollution
1971, pp. 140-151

Translated for EPA by
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THE PROBLEM OF SELECTING THE NUMBER OF SAMPLING POINTS AND FREQUENCY OF OBSERVATIONS OF ATMOSPHERIC POLLUTION

B.B. Goroshko

Sampling to determine atmospheric pollution and chemical analysis of the samples requires considerable expenditure of time. Therefore, the problem of the optimum number of sampling points and frequency of sampling is of considerable significance.

The task of investigating atmospheric pollution in the vicinity of individual sources is somewhat simpler. Let us deal with it initially, so that we can use this as a basis for moving on to the problem of organizing observations in urban territories with a great many sources emitting pollutants.

The problems of organizing the observation of atmospheric pollution around large enterprises have already been discussed in part [8-11]. It was noted that the minimum intervals between remote observations have been set at short distances. With increasing distance from the source, the intervals grow longer, so that on the lee side of the enterprise a significant influence is exerted by unorganized emissions and emissions from low stacks whose concentration decreases rapidly. In addition, it is felt that in the case of tall stacks concentration initially increases rapidly with distance from the source, reaches a maximum, and then decreases slowly [1, 4, 7, 17]. The largest concentrations, according to [1, 17], are found at distances from 10 H to 40 H with a maximum at approximately 20 H, where H is the height of the emission of pollutants. Consequently, it is necessary to perform more detailed observations at distances within the interval cited above. The necessity of observations at remote distances is a function of the intensity of the emission, the height of the sources, and the meteorological conditions

for dispersion of the pollutants. This can be established by calculating the expected values of concentration or experimentally on the basis of data from sample measurements.

At each distance, it is advisable to set up three-five sampling points 40-50 meters apart as a function of the width of the plume. This arrangement is necessary, because, even when the direction of the plume is stable, there are changes in its axis as a result of changes in the wind vector. With increasing distance from the source, the plume expands and thins out. In this case, determination of the direction of its axis is made more difficult, and in order to obtain the maximum axial concentrations it is necessary to increase the number of sampling points to at least five (the distance between them is increased to 200 meters, and sometimes more).

TABLE 1

Change in the Average Monthly Temperature Differential In the 0.5-2 Meter Layer in August

Weather	Period of Observations (hours)										
	0	4	6	8	10	12	14	16	18	20	22
Slightly cloudy	-0.4	-0.7	-0.5	0	0.8	1.2	1.6	0.7	-0.8	-0.8	-0.3
Overcast					0.6	0.7	0.8	0.4			

Beneath the plume from the source, which has a stable emission of pollutants, there is a daily pattern of concentrations affected by the changes in meteorological elements which determine the dispersal of pollutants. On this basis, we can formulate certain relationships for the purpose of determining the maximum concentrations. It has been shown theoretically [3] and by analyzing experimental data [7] that the level of concentration is largely influenced by changes in stratification, wind speed, and the degree of turbulence in the atmosphere. Recent studies indicate that there is a certain dangerous temperature gradient at which maximum concentrations at the ground are observed.

It is interesting to study the change in average monthly temperature differentials Δt in the 0.5-2 meter layer. Table 1 shows the average values of Δt for slightly cloudy weather, when the number of high and middle clouds during the observation period did not exceed 7 units and the amount of low clouds was no more than 3-4 units, as well as for cloudy weather. It is clear from the Table that the greatest changes are observed in the morning and evening with slightly cloudy weather: from 0800 to 1000, from 0 to 0.8°C and from 1600 to 1800 from 0.7 to -0.8°C. The considerable change Δt in the course of an hour indicates that, in the course of one hour's observation, it is possible to encounter cases when no dangerous conditions will be found. Consequently, in organizing the study of a source, it is necessary to sample no less than once an hour. Accordingly, meteorological observations must also be made hourly. It is particularly important to have increasingly frequent observations during periods when it is possible to have a maximum change in the gradient, i.e., during clear weather in daylight hours. On the whole, the organization of studying sources with high emission of pollutants during summer in the central band of the European territory of the Soviet Union necessitates sampling from approximately 0600 to 2100 hours in order to determine the most dangerous conditions with the maximum concentrations.

Under urban conditions, studying the chemical composition of the air is particularly complex, because the variations in the level of concentration at any given moment in time is a function of many factors which operate both constantly and change within wide limits in the course of 24 hours and even within one hour. The former include such factors as the size of the city, the relief of the terrain, the planning and the nature of the structures in the residential areas and the micrometeorological characteristics of the city, the presence of green areas, bodies of water, location of industrial sources, presence of organized and unorganized emissions, their height and temperature of the emerging gases. The second includes changes in the volume of pollutants reaching the atmosphere, the changes in the meteorological elements which determine the dispersion of the pollutants, the chemical stability of the elements and their physical properties, and periodically

functioning and random sources. All of these are typical in one way or another of a large industrial center and determine the degree of pollution of its air basin.

The air mass which moves over the territory of the city gradually becomes saturated with pollutants. Thus, the concentration will be less on the windward side the greater it is on the lee side. In this way, it is possible to measure the concentrations of sulfur dioxide in the northern part of Leningrad. With the wind blowing from the north, the maximum concentration was 3.5 to 4 times less than when the wind was from the south. The larger the size of the city, the longer the period of time a given air mass will be over its territory and therefore the concentration will increase that much more.

The layout of residential areas has an influence on their aeration. If the buildings are located close together, this will promote an increase in wind speed, i.e., the exchange of air will take place more slowly, and calm zones will form which correspond to accumulation of pollutants. This is particularly dangerous in the case of low emissions. Modern in-city construction, spaced far apart, is more favorable with respect to the exchange of air within the buildings and therefore leads to a decrease in concentration [13].

The microclimatic features of urban construction necessarily include a consideration of the heat island in the center of the city, and as a rule the construction of local air circulation directed toward the center of the city [5, 14]. Development of local circulation leads to the transfer of pollutants from the perimeter toward the center of the city and an increase in the concentration there.

Pollution sources in the city can be classified into two varieties on the basis of their location [6]: the first is composed of those which have the principal sources located in a single industrial area. The direction

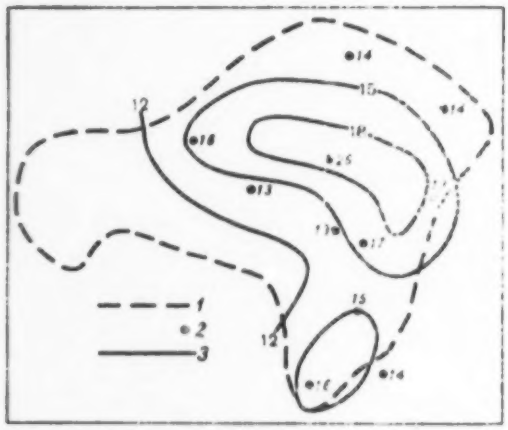

Figure 1. Distribution of Standardized Average Concentrations of Carbon Monoxide Over City During the Atuumn Period.

1 - city limits; 2 - sampling points; 3 - isolines of equal concentrations.

of the wind will naturally have an influence, due to the direction of the displacement of the principal plume in which the maximum concentrations will be found. The second type necessarily consists of those cities in which emission sources are scattered over the entire territory. In such cases, a general background of pollution of the air basin is produced which is quite uniform over the entire area.

Figure 1 shows the average concentration of carbon monoxide for a period in autumn (September-October) for one of the cities in the Ukraine. Inasmuch as the industrial enterprises are located all over the city and since carbon monoxide is emitted by motor vehicles in large amounts over the entire city, average concentrations will differ slightly in this territory. This method of classifying cities is of theoretical importance, because the method of organizing the observations which will make it possible to obtain reliable data depends upon it.

The height of pollution emission plays an important role in the development of the fields of concentration in the city. It is possible to divide

all sources conditionally into high and low. The high sources are stacks taller than 50 meters, while the low ones are stacks whose emission height is below 50 meters, as well as unorganized emissions. Concentrations increase in the zone of the plume of a high source with an increase in turbulent exchange. The decrease in turbulent exchange with establishment of inversion distribution of temperature and a low wind speed will lead to an increase in the concentrations at the ground with low and unorganized emissions of pollutants.

A number of authors [18, 22, etc.] state that the maximum concentrations are observed during calm or during nearly calm wind speed levels, but purification of the air basin occurs when the wind speed increases. These conclusions are valid when low emissions are present. This is confirmed, for example, by [15], which gives the dependence of the dust concentrations and the amount of sulfur dioxide on the wind speed during the warm and cold parts of the year. The two concentration maxima observed during a calm and at wind speeds of 4 to 6 m/sec. can be explained physically by the fact that, in the first case, the increase in concentration is promoted by low emissions, and in the second case — by emissions from all sources. The wind speed of 4 to 6 m/sec. was found to be dangerous for high sources located in urban areas. This led to the development of a secondary maximum. In other cases, the secondary maximum may not be observed. It has been shown theoretically [1,2] and by an analysis of experimental data [7] that the concentration levels in the region decrease with establishment of inversion distribution of temperature and with low wind speeds in the layer near the ground. In the city, when low sources are present, these conditions may lead to an increase in concentration as a result of a decrease in air exchange.

Because of other factors which determine the degree of pollution of a city, it is necessary to conclude that there are changes in the volume of pollution emissions in the atmosphere. In the first place they depend on the technological processes; in the second place, it is the periodicity of the work which is involved. Small enterprises which have low emissions as a rule

operate during the first half of the day. The emissions from motor vehicle traffic have their own specific nature. They are distributed and averaged over the entire city, with the most intensive emission of the pollutants occurring during the first half of the day. The burning of fuel in individual furnaces to heat residences occurs most frequently during the morning and evening hours. This process also has an annual cycle with a maximum during the winter months.

These facts complicate the development of firm principles for conducting work aimed at studying the pollution of the air basins of cities. This problem has been solved in different ways in various countries. Thus, for example, in the U.S.A. stations have been established for continuous recording of the principal ingredients. One such station is set up in a city, as a rule [19]. It is natural that with this kind of research organization the data which are obtained cannot characterize the atmospheric pollution for the entire year. In Nashville [23] a method of gradual approach to an optimum number of stations for monitoring the cleanliness of the air in the atmosphere was employed. During the initial period, 19 points were organized within the city for collecting samples over an area of 29 square miles. Later, as the data were collected and analyzed, it became clear that the samples that were collected at a number of points showed good agreement with respect to the levels of concentrations. Then one most characteristic point was selected, and the others were closed. In this way, the necessary optimum number of sampling points was determined. This method makes it possible to find the most representative sampling points for a given region of the city, but is very time consuming and costly.

In other cases, in order to establish a principle for organization of observations, the necessary number of sampling points, the frequency and total number of samples collected, use is made of the fact that the logarithmically normal distribution corresponds to the actual distribution regardless of the duration of a series of observations (week, month, year) and the type of pollutant [20]. Then the total recurrence will be expressed as follows:

$$F(Si) = \frac{1}{\sigma_1 \sqrt{2\pi}} \int_0^{Si} \exp\left[-\frac{(\lg S - a)^2}{2\sigma_1^2}\right] d(\lg S),$$

where F(Si) is the probability that the concentration of pollutant S will be less than Si; a is the average concentration logarithm; σ_1 is the standard deviation of the concentrations.

From this it follows that, in order to obtain the principal characteristics of pollution (average concentrations, maximum concentrations and recurrence), it is necessary to carry out successive measurements in a dense network of stations (at the corners of a square, 2 km x 2 km) with short duration of individual observations (from 20 to 30 minutes). In order to calculate the average concentration with an accuracy up to 20%, it is necessary to carry out at least 60 separate measurements, and the duration of the observations must not be less than a year. The day and hour of the individual observations should be selected by means of a table of random numbers.

The principal shortcoming of such a method of monitoring is that the data which are obtained make it possible to characterize the pollution of an urban atmosphere as a whole, on the basis of the values of the basic characteristics. This excludes the possibility of finding areas of maximum and minimum pollution. No consideration is given to the fact that the strict conditions for locating the sampling points (no further than 200 meters from a labelled grid) can lead to the points themselves being nonrepresentative, and in some cases this is simply impossible under urban conditions.

In other instances, when organizing observations [21], a geometric network for locating the sampling points is employed (Detroit, Windsor, Paris, Nashville). In Los Angeles, consideration was given to the trajectory of motion of air masses characteristic of the city.

The basic principles of organization of observations in the Soviet Union have been set forth briefly in [12] and in greater detail in [16]. They

indicate that the basis for monitoring is sampling at points which are organized so that one point occurs in an area measuring 10-20 km^2 on level ground, and one in every 5 to 10 km^2 of uneven terrain. Hence, in the first case the distance between the points will be approximately 3.2 to 4.5 km, and in the second — from 2.2 to 3.2 km. This frequency of points makes it possible to obtain characteristics of atmospheric pollution in microregions and cities as a whole. The organization of points according to this type of network, in our opinion, has a number of advantages. The lack of a fixed distance between points makes it possible to locate them in a more rational fashion. First of all, this applies to the selection of the more representative points. In addition, one can obtain a more detailed picture in the most polluted and populated areas through organization of a dense network of sampling points by reducing their numbers within the limits of the city to those points where the pollution is at a minimum.

The fact that a city may be located on uneven terrain makes it necessary to increase the number of sampling points due to the special relief conditions which promote stagnation of the air or development of local currents. Therefore, the sampling points must be located both in depressions and on elevations.

In order to check the above considerations, tests were performed to study a city which measures 25 to 30 km from north to south and about 20 km from west to east. Twenty-nine sampling points were organized in its territory, each one uniformly located in an area of 20 km^2. However, taking into account the location of the emission sources, inhabited areas, local relief, etc., the density in the most polluted area was one point for every 5 to 10 km^2 due to the decrease in density at the periphery of the city where there are small, partially built up settlements, a lack of large emission sources, and a large zone of green park areas. In addition, all 29 sampling points were moved to the northern part of the city whose territory was about one fifth of the total area of the city, where there formerly were seven sampling points. During the organization of the dense network of sampling points, the distance between them was 1 to 2 km.

On the basis of the data which were collected, the average monthly concentrations, recurrence of concentrations greater than certain values, and isolines of equal average monthly concentrations on the basis of the following ingredients were calculated: dust, sulfur dioxide, phenol, nitrous oxide, carbon monoxide. An analysis of the data will show that an increase in the number of sampling points did not make it possible to get a better idea of the principal characteristics with respect to either time or space.

In Table 2, for two cities in the Ukraine, we have shown the distance between points, and the deviation of the average monthly and maximum values of concentration in percent. It turns out that the distance between the points under urban conditions does not play the principal role and is not a critical factor in differentiating between the concentration values. Thus, for example, the distance between points (Point 1) 1 - 2, 7 - 8, 6 - 8, 5 - 9 varies from 2.6 to 3.6 km, while in the second city, with distances between points of 1.2 to 2.6 km, the differences in the concentrations do not exceed 40%, which is within the limits of accuracy of the method employed. In other cases, even with shorter distances, there are significant differences between the average, and particularly the maximum, concentrations.

In a detailed examination of the reasons for the changes in the concentration from one point to the other, it becomes clear that a difference exists mainly in the location of the sampling points, and to a lesser degree in the distance between them. In this sense, the principal influence is the proximity of busy roads and industrial areas. Hence, the density of a network with 3 to 4 km between points may be sufficient to obtain general characteristics of the field of concentration for the territory of the city. In this instance, when the concentration of pollutants is determined primarily by the influence of local sources, it is advantageous to carry out a sampling using automatic devices located at different distances from the center of the emissions.

TABLE 2

Excess Over the Average Monthly and Maximum Concentrations (in percent) in the Cities at Various Distances Between Points

Number of Points	Distance Between Points (km)	Excess Concentrations					
		Average			Maximum		
		Sulfur dioxide	Nitrous oxide	Phenol	Sulfur dioxide	Nitrous oxide	Phenol
				Point 1			
1.2	3.6	0	8	13	12	3	40
2.10	3.0	14	20	20	73	3	65
3.4	2.6	0	10	44	13	18	67
4.10	3.6	32	40	42	86	6	65
5.12	1.4	22	55	2	23	18	60
6.11	1.6	33	74	9	41	71	24
7.8	2.6	33	20	4	26	32	8
6.8	2.8	22	11	12	28	18	11
5.9	3.4	17	30	29	20	13	47
10.12	2.2	18	32	5	50	38	36
5.11	2.0	9	72	23	7	75	60
4.12	3.4	17	59	44	59	41	45
				Point 2			
2.12	1.2	2	12	4	18	19	9
3.12	2.4	7	10	7	16	18	20
4.5	1.2	11	12	3	49	0	80
5.6	1.5	10	9	15	8	20	85
6.9	1.2	7	23	10	33	3	30
7.8	1.2	10	2	3	8	16	2
8.9	1.5	16	16	0	37	10	13
9.13	1.5	18	16	46	18	15	31
10.11	1.1	8	0	0	35	63	6
11.12	1.8	2	5	13	7	43	3
12.13	3.0	33	10	54	29	23	23
6.13	0.8	24	7	27	10	13	2
2.14	2.6	18	7	22	0	9	23

A determination of the required frequency of sampling and the duration of the total working time for study is also very important.

On the basis of the fact that the meteorological elements and emission of pollutants change in the course of 24 hours, it is understandable that it is necessary to observe the concentration of pollutants with the greatest

possible coverage of daily variations. It may be assumed that these variations will be maximum during the daylight hours.

We know that meteorological elements and emissions in the atmosphere undergo maximum changes during daylight. These problems were discussed in [5, 6] where the dependence of concentration on the changes in meteorlogical elements on a daily and annual basis was shown; the height of the emission was also found to be a factor. The results obtained make it possible to conclude that sampling in a study of pollution of an air basin of a city must be carried out over an entire 24-hour period. More detailed observations should be carried out from 0600 to 2100 hours. By analogy with meteorological observations, we can recommend that the time interval between sampling be three hours. In order to reduce the number of observers, a sliding graph is proposed, i.e., three days a week during the first half of the day and three days a week in the second, alternating every other day. The data which we obtained indicate that using this kind of a graph is justified. It is natural that the maximum values will not always be shown on such a graph of observations. This can be seen, for example, from the data in Table 3. It was compiled on the basis of hourly 20-minute samplings of sulfur dioxide at one of the points in a city in August, 1969. The data in the second column characterized the daily maximum concentrations from all of the observation periods; the third gives the values if the sampling were performed during daylight hours (at 0700, 1000, 1300, 1400, 1700 and 2000); the fourth column shows the deviation of concentrations in the third column from those in the second; the fifth column was for sampling according to the sliding graph, i.e., one day at 0700, 1000 and 1300, and on the other day at 1400, 1700 and 2000; the seventh, eighth and ninth columns give the average concentrations, respectively, for all of the periods during daylight hours and according to the sliding scale, while the tenth and eleventh columns give the deviations from average values for all periods.

TABLE 3

Maximum and Average Standardized Concentrations of Sulfur Dioxide (mg/m^3) and Their Deviation at Different Sampling Frequencies in Percent (Point 1)

No.	Maximum from all periods	Maximum from periods 7, 10, 13, 14, 17, 20	Deviation %	Maximum along the sliding graph	Deviation (%)	Daily Average for all periods	Daily average for periods 7, 10, 13, 14, 17, 20	Deviation (%)	Daily average on the sliding scale	Deviation (%)
1	2	3	4	5	6	7	8	9	10	11
1	0.56	0.50	11	0.50	11	0.29	0.29	0	0.37	-28
2	0.25	0.23	8	0.23	8	0.18	0.18	0	0.19	- 6
3	1.01	1.01	0	1.01	0	0.90	0.94	-4	0.94	- 4
4	0.61	-	-	-	-	0.60	-	-	-	-
5	1.34	1.34	0	0.40	70	0.45	0.53	-18	0.27	40
6	0.52	0.33	37	0.33	37	0.25	0.19	24	0.21	16
7	0.78	0.78	0	0.78	0	0.46	0.46	0	0.46	0
8	0.13	0.13	0	0.12	8	0.09	0.08	11	0.06	33
9	0.46	0.46	0	0.46	0	0.27	0.31	-15	0.31	-15
10	0.23	0.10	56	0.10	56	0.11	0.07	36	0.03	73
11	0.28	0.17	39	0.17	39	0.09	0.07	22	0.06	33
12	0.35	0.35	0	0.31	11	0.22	0.25	-14	0.24	- 9
13	0.66	0.53	20	0.53	20	0.44	0.46	- 5	0.49	-11
14	0.43	0.43	0	0.43	0	0.32	0.34	- 6	0.35	- 9
15	0.28	0.28	0	0.23	18	0.19	0.20	- 5	0.17	10
16	0.68	0.51	25	0.51	25	0.26	0.22	15	0.26	0
17	0.38	0.38	0	0.28	26	0.21	0.20	5	0.16	24
18	0.34	0.33	3	0.33	3	0.17	0.15	12	0.18	- 6
19	0.28	0.28	0	-	-	0.12	0.21	-75	-	-
20	0.24	0.24	0	0.10	58	0.09	0.10	-11	0.03	67
21	0.52	0.51	2	0.47	10	0.35	0.36	- 3	0.30	14
22	0.33	0.33	0	0.21	36	0.16	0.17	- 6	0.14	12
23	0.69	0.69	0	0.23	67	0.11	0.19	-73	0.13	-18
24	0.23	0.17	26	0.17	26	0.12	0.09	25	0.09	25
For the month	1.34	1.34	0	1.01	25	0.25	0.25	0	0.24	4

From this Table it follows that selection of the maximum values from the monthly data and the calculation of the average monthly concentrations constitutes a satisfactory characterization of the de ree of atmospheric pollution for sampling according to the sliding table. Deviation of the maximum and average monthly concentration values, with six fold sampling and according to a sliding graph, from the values for hourly sampling does not exceed the error of the method of determining the given ingredient. There is a less satisfactory agreement between the maximum and average daily concentrations at different sampling frequencies. However, a detailed examination of the Table will show that the maximum percentage of deviation is observed at low values of concentration, when the error increases. Similar results were obtained at two other points in the same city in the sampling of sulfur dioxide, nitrous oxide, phenol, carbon monoxide and dust at all three points.

The data which were obtained indicate that the field of concentration of the various ingredients shows a certain degree of inertia. This makes it possible to recommend that, in order to obtain the basic pollution characteristics of the atmosphere, the sliding graph for air sampling over the territory of the city should be used.

In order to reduce the omission of maximum concentrations, it is advantageous to use automatic devices for sampling beneath the plumes of the principal sources of pollution.

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